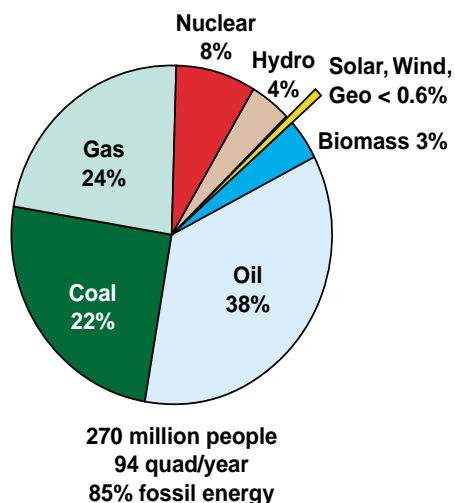# 2 SEPARATION AND CAPTURE OF CARBON DIOXIDE

2.1 CHARACTERIZATION OF CARBON FLOWS (SOURCE TERMS)

This chapter and road map address the separation and capture of anthropogenic CO_2 only. Separation and capture have been identified as a high-priority topic in other reports (Socolow 1997; Herzog 1998; FETC 1998). The costs of separation and capture, including compression to the required pressure for the sequestration option used, are generally estimated to make up about three-fourths of the total costs of ocean or geologic sequestration (Herzog 1998). A study conducted for the IEA Greenhouse Gas R&D Programme suggests that significantly increased power generation costs will result from CO_2 separation and capture (IEA 1998). Using a base case pulverized coal plant with flue gas desulfurization for comparison, the cost of eliminating CO_2 emissions from advanced power generation plants ranged from \$35 to \$264 per tonne of CO_2, and power cost increases ranged from 25 to 215 mills/kWh.

The wide range of costs is indicative of the peculiarities of the advanced power generation plants and the wide range of separation and capture possibilities. Although some of the more expensive methods may be used in certain production enterprises with high–value-added products, the less expensive approaches will likely be used in conventional and advanced power plants. These less expensive approaches are appropriate for power generation, and an independent analysis (Herzog 1998) suggests these separation and capture approaches would increase power generation costs by about 20 to 30 mills/kWh.

The scope of this element of the road map includes all anthropogenic emissions of CO_2, with a focus on those sources most amenable to various

Primary Energy Sources

Nuclear 8%
Hydro 4%
Solar, Wind, Geo < 0.6%
Gas 24%
Biomass 3%
Coal 22%
Oil 38%

270 million people
94 quad/year
85% fossil energy

This chart depicts energy use in the United States by primary energy sources. For the last 4 years, coal production in the United States has been at record levels of over a billion short tons per year. Most of the coal is consumed in power generation, as is some natural gas. Most of the natural gas is used for space heating and other domestic, commercial, and industrial applications. The great majority of oil produced is used for transportation, and essentially none is used for electricity generation. This road map focuses on the CO_2 sources most adaptable to separation and capture; these include, primarily, power generation, hydrogen production, natural gas production, refineries, and industrial processes.

separation and capture methods. Sources that appear to lend themselves best to separation and capture technologies include large-point sources of CO_2 such as conventional pulverized-coal steam power plants; natural-gas-fired combined cycle plants; and advanced power generation systems, including coal or natural gas combustion plants employing enriched air or oxygen to support combustion with CO_2 recycling, integrated coal gasification (especially oxygen-based) combined cycles, hydrogen turbines, and fuel cells. Many of the advanced systems will use enriched air or oxygen to support the combustion process. The reduction or elimination of the large volume of diluent nitrogen in process and flue gases dramatically improves the opportunity for the separation and capture of CO_2 from these systems. The equipment used for combustion and processing will range from existing technology (e.g., coal-fired steam plants and gas turbines) to advanced technology (e.g., production of hydrogen from fossil fuels).

In addition to power plants, numerous other high-CO_2-emitting industrial sources are being considered for application of capture and sequestration technologies. In natural gas production, CO_2 is often generated as a by-product. Natural gas may contain significant amounts of CO_2 (20% or more by volume), most of which must be removed to produce pipeline-quality gas. Therefore, sequestration of CO_2 from natural gas operations is a logical first step in applying CO_2 capture technology, as demonstrated by the Sleipner West project in Norway, the proposed Natuna project in Indonesia, and the proposed Gorgon project in Australia. Other significant industrial sources of CO_2 include oil refineries, iron and steel plants, and cement and lime producers. Although these sources contribute only a small fraction of total CO_2 emissions, separation and capture of these emissions are feasible and would contribute significantly to overall CO_2 emission reduction goals.

Dispersed sources of CO_2 emissions, particularly residential buildings and mobile spark ignition and diesel

Advanced Power Plants

Advanced coal-fired power plants, such as this 800-ton-per-day coal gasification pilot/demonstration plant, will have energy conversion efficiencies 20 to 35% higher than those of conventional pulverized coal steam plants. These advanced plants are also much more amenable to carbon management than are conventional plants. *(Photo courtesy of Tom Lynch of Dynegy)*

engines, are especially challenging sources for applying cost-effective separation and capture methods. Although these sources are collectively large, they are not a primary focus of our road map. However, the introduction of fuel cells for vehicular propulsion and power generation may occur within the time frame of this road map, and depending on the extent of their deployment, the need to use fossil fuels to produce hydrogen (H_2) for fuel cells could have a significant impact on CO_2 separation and capture. For example, if buses and vehicle fleets move toward on-board H_2 storage, central H_2 production facilities may be built that would allow CO_2 separation and capture. Such central H_2 production facilities are considered in this road map. Other advanced power systems, such as hydrogen turbines that would use H_2 as fuel, also have

important implications with respect to the need for central H_2 production facilities and the opportunity for CO_2 separation and capture. Electric vehicles may also come into widespread use during the time frame of this road map. Should that occur, separation and capture of CO_2 at the central power stations that produce the electricity for recharging electric vehicle batteries would indirectly reduce CO_2 emissions from the transportation sector. However, one of the consequences of the deregulation of the electric power industry may be the introduction of a significant distributed power supply. Depending on the size and nature of these power generation plants, such a change might have a negative impact on the ability to separate and capture CO_2.

Carbon dioxide concentrations in effluent streams will range from ~5% for current power generation plants to almost 100% for some advanced technologies. All separation and capture feed streams are likely to contain small amounts of impurities such as oxygen, sulfur oxides, and nitrogen oxides from combustion of natural gas or advanced processing of fossil fuels to yield hydrogen. For some current and emerging technologies involving combustion of coal, the feed streams will contain large amounts of nitrogen, oxygen, water vapor, particulates, and volatile and semivolatile chemical species as well. The feed stream may also be contaminated with chemicals used to remove other constituents (e.g., sulfur or nitrogen oxides). Feed-stream pressures will range from essentially ambient for current technologies to tens of atmospheres for some advanced processes. Feed-stream temperatures will range from very warm (~50°C) to hot (hundreds of degrees).

2.2 CURRENT AND POTENTIAL SCIENCE AND TECHNOLOGY REQUIREMENTS

The goal of CO_2 separation and capture is to isolate carbon from its many sources in a form suitable for transport and sequestration. The technology required to perform this function depends on the nature of the carbon source and carbon form(s) that are suitable for subsequent steps leading to sequestration. Many forms are possible, including gaseous and supercritical CO_2 and even clathrates. High levels of purity (99+%) are possible, but at significant cost.

The impurities in the product must be of sufficiently low concentrations that transportation and sequestration operations are not compromised. The purity requirements imposed by sequestration operations are not known because sequestration technology is being developed concurrently. Some initial investigation to develop provisional purity requirements will be necessary and will be reviewed and modified as the requirements of various sequestration options become clear. End-state specifications may be for the final product of separation and capture or for an intermediate product that is converted to another form (e.g., a carbonate) before transport. Separation and capture processes that operate on effluent streams, as well as those that are integral elements of optimized advanced processing flow sheets, will be considered.

2.3 CURRENT AND POTENTIAL SCIENCE AND TECHNOLOGY CAPABILITIES

Categorized in this section are what are believed to be conventional separation and capture options that are applicable for anthropogenic CO_2 emissions. It is not presumed that the categories or methods within the categories are exhaustive; certainly, little-known or as-yet-unknown techniques could ultimately become preferred options. For those CO_2 separation and capture methods identified, performance characteristics, including CO_2 product purity and operating conditions, differ because of operational or technical considerations. These characteristics of CO_2 separation and capture technologies are the basis for matching them with the technologies that are the anthropogenic sources of CO_2.

The most likely options currently identifiable for CO_2 separation and capture include

- chemical and physical absorption
- physical and chemical adsorption
- low-temperature distillation
- gas-separation membranes
- mineralization and biomineralization
- vegetation

These were identified and included as probable options because of process simplicity, environmental impact, and economics. Currently, several CO_2 separation and capture plants use one or more of these methods to produce CO_2 for commercial markets. The vegetation separation and some mineralization methods are also sequestration methods and are discussed in the appropriate focus area chapters.

2.3.1 Chemical and Physical Absorption

Carbon dioxide can be removed from gas streams by physical or chemical absorption. Physical absorption

processes are governed by Henry's law (i.e., they are temperature and pressure dependent with absorption occurring at high pressures and low temperatures). Typically, these processes are used when the concentration (i.e., partial pressure of CO_2) is high (>525 kPa). The removal of 0.1 to 6% CO_2 from natural gas production wells by chemical absorption using amines can be deployed conveniently in remote fields. Currently, this approach represents the most widely deployed commercial technology for capture. However, in other commercial applications, the typical solvents for physically absorbing CO_2 include glycol-based compounds (e.g., the dimethylether of polyethylene glycol) and cold methanol.

Chemical absorption is preferred for low to moderate CO_2 partial pressures. Because CO_2 is an acid gas, chemical absorption of CO_2 from gaseous streams such as flue gases depends on acid-base neutralization reactions using basic solvents. Most common among the solvents in commercial use for neutralizing CO_2 are alkanolamines such as monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA). Other chemical solvents in use are ammonia and hot potassium carbonate. Flue gases are typically at atmospheric pressure. Depending on the CO_2 content of the flue gas, the partial pressure of CO_2 can vary from 3.5 to 21.0 kPa. At such low partial pressures, alkanolamines are the best chemical solvents to enable good CO_2 recovery levels; however, use of these solvents must be balanced against the high energy penalty of regenerating them using steam-stripping.

Flue gases typically contain contaminants such as SO_x, NO_x, O_2,

Sleipner T Platform

The Sleipner T (T = treatment) platform in the North Sea is used by Statoil, the Norwegian state oil company, to remove CO_2 from sub-quality natural gas. An amine absorption process is used to remove the CO_2, which is then compressed and piped to the adjacent Sleipner A platform for injection into the Utsira formation 1000 m below the seabed (see Chap. 5). Sleipner T is representative of the absorption technology that could be used for separation and capture of CO_2, and it is used specifically as a CO_2 mitigation strategy. This is the largest CO_2 separation, capture, and sequestration operation in the world, sequestering about a million tonnes of CO_2 per year. *(Photo courtesy of Olav Kaarstad of Statoil.)*

CO$_2$ Separation in Hydrogen Production

Separation of CO$_2$ and other contaminant gases using adsorption systems is a commercial practice in the production and purification of hydrogen. The reformer hydrogen plant shown produces 35 million standard cubic feet of hydrogen and about 9 million standard cubic feet of CO$_2$ per day. These plants are not usually operated in a mode that results in complete conversion of methane to hydrogen and CO$_2$. However, operational modifications could be made in which essentially pure hydrogen and CO$_2$ would be produced. Numerous plants such as this one are in use worldwide, but the CO$_2$ is typically vented to the atmosphere. *(Photo courtesy of Joe Abrardo of Air Products and Chemicals)*

hydrocarbons, and particulates. The presence of these impurities can reduce the absorption capacity of amines as well as create operational difficulties such as corrosion. To avoid such problems, these contaminants are often reduced to acceptable levels through the use of suitable pretreatment techniques. Some commercial processes handle these difficulties through pretreatment and/or the use of chemical inhibitors in the absorption process. However, these processes tend to be more expensive than conventional alkanolamine-based absorption processes.

Some of the typical operating problems encountered in using conventional trayed or packed columns for gas-liquid contact are foaming, vapor entrainment of the solvent, and the need to replenish the solvent in low quantities. However, these problems have a relatively small effect on the total system costs of the alkanolamine-based absorption process. Membrane contactors that typically use polymeric membranes can offer some advantages over conventional contactors, which are expected to be most advantageous where system size and weight need to be minimized (e.g., on ocean platforms). Potential benefits include the elimination of foaming and vapor entrainment, as well as the ability to maintain liquid and gas flow rates independently.

2.3.2 Physical and Chemical Adsorption

Selective separation of CO$_2$ may be achieved by the physical adsorption of the gas on high-surface-area solids in which the large surface area results from the creation of very fine surface porosity through surface activation methods using, for example, steam, oxygen, or CO$_2$. Some naturally

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occurring materials (e.g., zeolites) have high surface areas and efficiently adsorb some gases. Adsorption capacities and kinetics are governed by numerous factors including adsorbent pore size, pore volume, surface area, and affinity of the adsorbed gas for the adsorbent.

An IEA study (1998) evaluated physical adsorption systems based on zeolites operated in pressure swing adsorption (PSA) and thermal, or temperature, swing adsorption (TSA) modes. In PSA operation, gases are adsorbed at high pressures, isolated, and then desorbed by reducing the pressure. A variant of PSA, called vacuum swing adsorption, uses a vacuum desorption cycle. In TSA operation, gases are adsorbed at lower temperatures, isolated, and then desorbed by heating. These processes are somewhat energy-intensive and expensive. The IEA report concludes that PSA and TSA technologies are not attractive to the gas- and coal-fueled power systems included in that study. Nevertheless, PSA and TSA are commercially practiced methods of gas separation and capture and are used to some extent in hydrogen production and in removal of CO_2 from subquality natural gas. Therefore, these methods clearly are applicable for separation and capture of CO_2 from some relatively large-point sources.

2.3.3 Low-Temperature Distillation

Low-temperature distillation is widely used commercially for the liquefaction and purification of CO_2 from high-purity sources (typically a stream with >90% CO_2). In low-temperature distillation, a low-boiling-temperature liquid is purified by evaporating and subsequently condensing it. However, such processes are not used for separating CO_2 from significantly leaner CO_2 streams. The application of

distillation to the purification of lean CO_2 streams necessitates low-temperature refrigeration (<0°C) and solids processing below the triple point of CO_2 (–57°C). A patented process to separate CO_2 from natural gas, providing liquid CO_2, is an example of such a low-temperature process (Valencia and Denton 1985; Victory and Valencia 1987).

Distillation generally has good economies of scale, as it is cost-effective for large-scale plants, and it can generally produce a relatively pure product. Distillation is most cost-effective when feed gases contain components with widely separated boiling points, and when the feed gas is available at high pressure and most of the products are also required at high pressure. Low-temperature distillation enables direct production of liquid CO_2 that can be stored or sequestered at high pressure via liquid pumping. The major disadvantage of this process is that, if other components are present that have freezing points above normal operating temperatures, they must be removed before the gas stream is cooled to avoid freezing and eventual blockage of process equipment. Another disadvantage is the amount of energy required to provide the refrigeration necessary for the process.

Most CO_2 emissions being considered for CO_2 capture are produced in combustion processes. Such streams contain water and other trace combustion by-products such as NO_x and SO_x, several of which must be removed before the stream is introduced into the low-temperature process. These by-products are usually generated near atmospheric pressure. These attributes, coupled with the energy intensity of low-temperature refrigeration, tend to make distillation

less economical than other routes. The application of low-temperature distillation, therefore, is expected to be confined to feed sources at high pressure and with high CO_2 concentrations (e.g., gas wells).

2.3.4 Gas-Separation Membranes

Gas-separation membranes are of many different types, and although the efficacy of only a few of these types in separating and capturing CO_2 has been demonstrated, their potential is generally viewed as very good. Diffusion mechanisms in membranes are numerous and differ greatly depending on the type of membrane used. Generally, gas separation is accomplished via some interaction between the membrane and the gas being separated. For example, polymeric membranes transport gases by a solution-diffusion mechanism (i.e., the gas is dissolved in the membrane and transported through the membrane by a diffusion process). Polymeric membranes, although effective, typically achieve low gas transport flux and are subject to degradation. However, polymer membranes are inexpensive and can achieve large ratios of membrane area to module volume.

Palladium membranes are effective in separating H_2 from CO_2, but gas fluxes are typically very low, and palladium is subject to degradation in sulfur-containing environments. Porous inorganic membranes, metallic or ceramic, are particularly attractive because of the many transport mechanisms that can be used to maximize the separation factor for various gas separations. Porous inorganic membranes can be 100 to 10,000 times more permeable than polymeric membranes. (Permeance is the volume of gas transported through a membrane per unit of surface area per unit of time per unit of differential pressure.) However, the cost for inorganic membranes is high, and the ratio of membrane area to module volume is 100 to 1000 times smaller than that for polymer membranes. These factors tend to equalize the cost per membrane module. The inorganic membrane life cycle is generally expected to be much longer. Inorganic membranes can be operated at high pressures and temperatures and in corrosive environments, yet still have very long life cycles. They are also less prone to fouling and can be used in applications where polymer membranes cannot.

Considerable interest and R&D are being focused on zeolite-type materials to achieve a membrane with molecular sieving characteristics. However, the permeance of such membranes tends to be substantially lower than desired. These are high-cost membranes because the methods for fabricating them are expensive.

Inorganic membranes can be made with effective pore diameters as small as 0.5 nm and as large as desired. Membranes can be made with a wide range of materials, and pore size and material can be changed to improve permeance and separation factor. Large separation factors are essential to achieve desired results in a single stage. Inorganic membranes can be made to separate small molecules from larger molecules (molecular sieves) or to separate certain large molecules from smaller molecules (enhanced surface flow). This latter effect is important because it allows separation that will keep the desired gas either on the high-pressure or the low-pressure side of the membrane. Note that the operating conditions play an important role in determining the change in

mole fraction across a membrane and the amount of the desired gas that can be recovered (captured). There must be a partial pressure gradient of the desired gas across the membrane to achieve a flow of that gas through the membrane.

With all the design parameters available, it is likely that an inorganic membrane can be made that will be useful for separating CO_2 from almost any other gas if appropriate operating conditions can be achieved. However, for multiple gas mixtures, several membranes with different characteristics may be required to separate and capture high-purity CO_2.

2.4 SCIENCE AND TECHNOLOGY GAPS

We present here our views on the gaps in science and technology and the R&D required to fill or span these gaps in order that our vision may be achieved. As a result in large measure of the state of separation and capture technology, the R&D projects required to address these needs will be of the type that has been described as "Pasteur's Quadrant" research. This type of research seeks to extend the frontiers of understanding but is also inspired by considerations of use. We extend that description somewhat in that our R&D recommendations refer to a science-based technology development approach.

2.4.1 Chemical and Physical Absorption

The issue of the recovery of volatile trace elements, such as mercury, in fossil fuel is a factor in the regulatory process and must be considered in the context of this road map. The optimal recovery strategy for trace elements may not be consistent with an optimal strategy for CO_2 capture. Also, using current technologies, minimizing energy costs for CO_2 capture will probably not be compatible with a 100% CO_2 capture strategy. Better options must be developed to reduce total system costs for CO_2 recovery. Specific needs are listed below.

- Significant development work on membrane contactors is needed to improve their chemical compatibility with alkanolamines and high-temperature resistance, as well as to lower costs.
- Commercially available alkanolamines such as MEA, DEA, and MDEA have different costs, rates of reaction with CO_2, absorptive capacities, and corrosion rates. Researchers have an opportunity to optimize existing solvents or develop new solvents to reduce total capital and operating costs. Some development of chemical and physical solvents and systems will be required to achieve the vision of this road map.
- It is likely that novel solvents and system components will reduce the capital and energy costs for flue gas treatment to separate and capture CO_2. Prudent courses of action include investment in R&D on novel solvents, particularly those amenable to use in advanced systems, and investment in system studies to identify the best possible configurations of processes and equipment, particularly as they relate to cost and process simplicity.
- Considerable interest has been shown in the concept of retrofitting conventional pulverized-coal boilers for CO_2 recycling to increase the CO_2 concentration to the point where recovery becomes economically feasible.

- Molecular modeling of the absorption process is indicated to aid in the selection of absorbents.
- Kinetic modeling is needed to establish or confirm rate-limiting steps in the absorption process.
- Synthesis of absorbents based in part on molecular and kinetic models is an appropriate R&D investment.
- Systems that use air to support combustion present difficulties in separation and capture of CO_2 because of the large amount (~80%) of nitrogen diluent in the process stream. Integrated gasification combined cycle (IGCC) power plants could provide an ideal opportunity for CO_2 capture when oxygen rather than air is used to support the gasification process. (In combined cycles, which include gas turbines and steam turbines, the hot exhaust gases from the gas turbines are used to generate steam to drive the steam turbines.) Coal-derived gas for gas turbines is produced in a highly concentrated, pressurized form that allows for the use of a variety of solvents that can capture CO_2 from the gas stream before combustion, which may also be in oxygen rather than air. As a baseline case, the cost and energy benefits of chemical absorption processes integrated into an IGCC or other advanced power system must be demonstrated in a commercial setting as a real-case option.
- Novel gas/liquid contactors must be developed to minimize mass- and heat-transfer effects in gas scrubbing. The contactors might take advantage of so-called "structured packing" or even "microchannel reactors." Using microchannel hardware, highly compact and efficient absorption

systems could be developed that consist of an absorber/heat exchanger and desorber. Because the dimensions of the channels are measured in micrometers, heat- and mass-transfer effects are limited. Isothermal operation could produce higher absorption capacity. The technical challenges for microchannel reactors will be cost containment, prevention of plugging, and high throughput. Other potential problems include scale-up, corrosion, and solvent carryover.

2.4.2 Physical and Chemical Adsorption

H_2 production plants that use PSA produce an impure CO_2 stream containing unrecovered hydrogen, methane, CO, and nitrogen. This stream is recycled to the reformer as fuel, becoming the flue gas from the reformer. Physical adsorbents suffer from low selectivity and low capacity, and they are limited to operation at low temperatures.

- Adsorbents that can operate at higher temperatures in the presence of steam must be developed and are already under consideration.
- Indicated programs include R&D aimed at the synthesis of adsorbents with increased adsorptive capacity and improved kinetics and capable of producing a pure CO_2 product, as well as R&D directed to improving methods for effecting the adsorption-desorption process.
- Molecular modeling of adsorbents is needed to aid in the identification of adsorbents selective to CO_2.

- Kinetic modeling to identify rate-limiting steps and to provide a focus for adsorbent development is needed.
- New steam-tolerant, high-temperature sorbent materials need to be developed and coupled with novel process concepts. Unlike zeolites and other inorganic sorbents, these sorbent materials would be capable of adsorbing CO_2 in the presence of steam. The sorbent would be regenerated in a low-energy-intensive manner. Regenerability would eliminate material-handling problems when nonregenerable natural minerals are used. Stability of the sorbent over thousands of cycles needs to be demonstrated.
- Other novel adsorption concepts for CO_2 separation and capture are likely, and R&D on novel concepts should be pursued. If adsorbents can be developed that are capable of adsorption at high temperature and desorption using novel processes, they could significantly improve the ability to control CO_2 emissions from fossil-fueled power systems.

2.4.3   Low-Temperature Distillation

To extend the viability of low-temperature distillation processes, several development activities would be required.

- Process cycle development and process integration studies for specific applications are needed.
- Integration with sequestration processes and development of efficient and novel refrigeration cycles may enable competitive low-temperature distillation processes. Comparison with other technology options will ultimately depend on the specific application and opportunity.

2.4.4   Gas-Separation Membranes

Considerable R&D is required to realize the potential of membranes for separation and capture of CO_2, particularly at higher temperatures and pressures.

- R&D on polymeric membranes is essentially restricted to changing the composition of the polymer to increase the dissolution and diffusion rates for the desired gas components.
- Experience has shown an apparent limit to the effectiveness of polymeric membranes. The polymer composition can be changed to increase the membrane permeance, which invariably decreases the separation factor. The converse is also true: changing the composition to increase the separation factor reduces the membrane permeance. Although there is not nearly so extensive an accumulation of data for inorganic membranes, the available data do not indicate a corresponding relationship for inorganic membranes.
- R&D in molecular modeling is needed to indicate the potential of membranes to separate CO_2.
- Kinetic modeling should be used to establish the potential flux of gases in membrane systems.
- Novel membrane synthesis methods should be developed.
- Inorganic, palladium-based membrane devices could be developed that reform hydrocarbon fuels to mixtures of hydrogen and CO_2 and that, at the same time, separate the high-value hydrogen. The remaining gas, predominantly CO_2, would be recovered in a compressed form. The hydrogen could be used in future fuel cell systems or advanced turbine power systems. Pure hydrogen, when

burned to generate power, produces water vapor as the only product of combustion. Daunting issues include capital costs and stabilization of the membrane in highly corrosive gases if coal is used.

2.4.5 Product Treatment and Conversion

As noted previously, the product of the separation and capture function will be CO_2. However, the attributes of the CO_2, such as its concentration, impurities, pressure, and temperature, will differ for the respective combinations of sources and separation and capture methods employed. Absorption processes, for example, may be manipulated to yield CO_2 streams of very high purity, and those CO_2 streams will generally be at source pressures. For those options that will sequester carbon as CO_2, it is assumed that the CO_2 will be subjected to the purification treatment and pressurization required for transportation and for sequestration. The CO_2 product may be provided at 90 to 99+% purity, at temperatures ranging from cryogenic to a few hundred degrees Celsius, and at pressures from atmospheric to more than 3.5 MPa. Different carbon forms (other than CO_2) may also be required for some of the sequestration options. R&D should address

- full-cycle analysis of product treatment and conversion to meet the requirements of transportation and sequestration
- conversion of CO_2 to the required form for the particular sequestration option
- the disposition of the variety of by-products that may be produced during conversion of the CO_2 to other products

2.4.6 Transportation

In some scenarios, the separation and capture process will be remote from the sequestration process. Any R&D program must include carbon transport to the sequestration site and should address primarily systems aspects such as optimization and integration of the carbon sources, separation and capture, transportation, and sequestration. The cost to build a CO_2 pipeline today is estimated to be in the range of $1–10 per tonne of CO_2 per 100 miles. All costs associated with the pipeline, such as right of ways and repairing crop damage, are included. However, this estimate assumes that the pipeline does not have any river crossings and avoids urban areas (Fox 1999).

2.4.7 Advanced Concepts

This section addresses advanced concepts that have been identified and/or advocated as having significant potential for CO_2 separation and capture. In one advanced concept, CO_2-containing gases are dissolved in water, followed by the formation of CO_2 hydrates in which CO_2 is trapped in a crystalline ice-like solid. The process requires gases at about 0°C and 1 to 7 MPa, depending on the other gases present and on the partial pressure of CO_2 in the gas stream. The formation of CO_2 hydrates may be especially amenable to removal of CO_2 from pressurized gas streams with minimal energy losses.

An advanced approach, called electrical swing adsorption (ESA), that addresses many of the issues of PSA and TSA systems uses a novel carbon-bonded activated carbon fiber as the adsorption medium (Burchell et al. 1997). Activation conditions for these adsorbents may be varied to increase

or decrease pore size, pore volume, and surface area to improve the effectiveness of the carbon fiber as a CO_2 adsorbent. This material is also highly conductive electrically, so adsorbed gases can be rapidly, effectively, and efficiently desorbed by passing a low-voltage electrical current through the material. This adsorption-desorption process may be used with no variation of system pressure and with minimal variation in system temperature. The electrical energy required for desorption is approximately equal to the heat of adsorption of the adsorbed gas; thus the ESA process is promising as an energy-efficient, economical gas separation and capture method.

Another novel technology is referred to as "chemical-looping combustion," or more recently as "sorbent energy

transfer." In this process, the fossil fuel (gasified coal or natural gas) transfers its energy to reduce a metal oxide, producing steam and high-pressure CO_2 that can be sequestered with little additional compression energy. The steam is used in a steam turbine to produce electricity. The metal is then reoxidized in air, producing heat to raise the temperature of a high-pressure stream of air or nitrogen to drive a gas turbine to generate more electricity. The oxidized metal is sent to the reducing vessel to repeat the cycle. The barriers to any new combustion system are legion; this is also true even of conventional coal combustion using oxygen instead of air with CO_2 recycling.
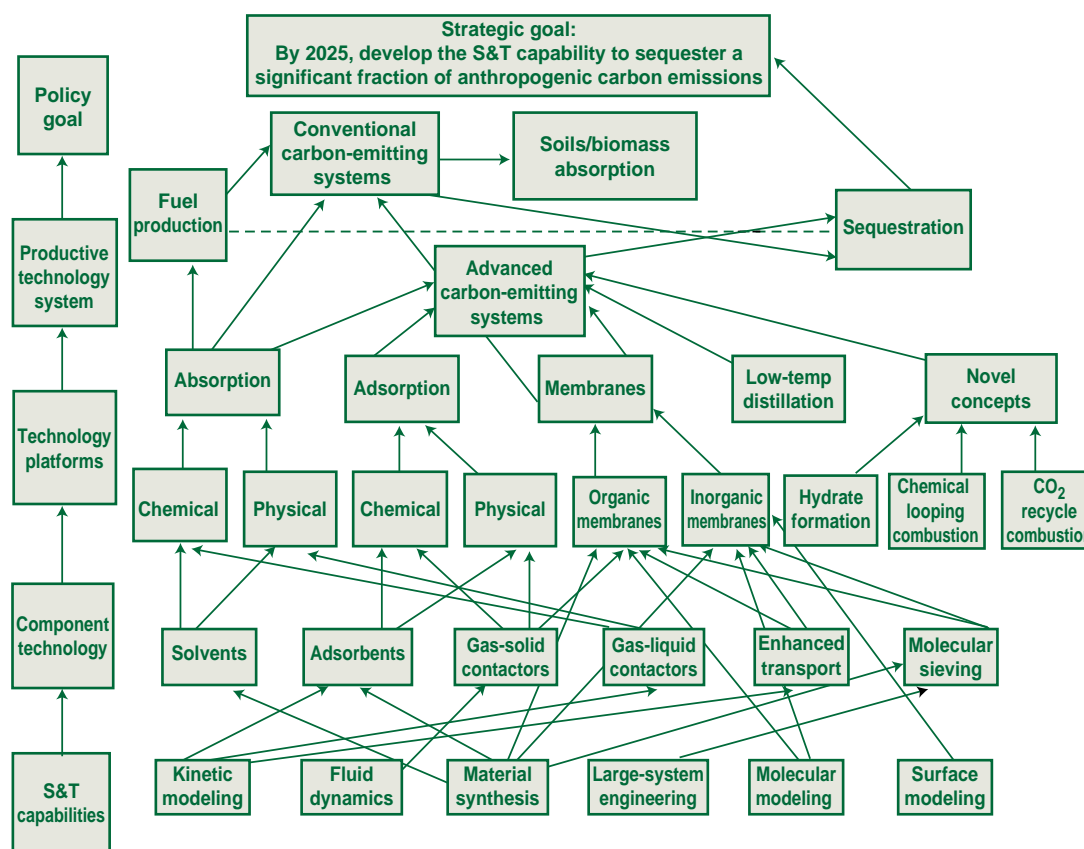

Fig. 2.1. Separation and capture R&D road map.

2.5 ALIGNMENT OF REQUIREMENTS TO CAPABILITIES (R&D ROAD MAP)

As indicated in the preceding section, numerous R&D needs and opportunities exist for improvements and innovations related to CO_2 separation and capture. Figure 2.1 presents an R&D road map for pursuing the stated goal. Based on the analysis presented here, as well as analyses presented in the references to this chapter, separation and capture of CO_2 from anthropogenic sources for sequestration via any of several options appear to be possible. Notwithstanding this possibility, a disciplined R&D program directed to improvements in currently available technology, extension of current developments, and pursuit of innovative and novel approaches is critical to ensuring the ability to effectively and efficiently capture CO_2 at costs that are not prohibitive.

2.6 REFERENCES

Burchell, T. D., R. R. Judkins, M. R. Rogers, and A. M. Williams 1998. "A Novel Process and Material for the Separation of Carbon Dioxide and Hydrogen Sulfide Gas Mixtures," *Carbon*, 35(9): 1279–94.

FETC (Federal Energy Technology Center) 1998. *Proceedings of the Government Workshop on Carbon Sequestration*, Morgantown, West Virginia, July 23–24, 1998 (forthcoming).

Fox, C. E. 1999. Personal communication from C. E. Fox, Vice-President of Operations and Technology, Shell CO_2 Co. Ltd., to H. J. Herzog, Massachusetts Institute of Technology, October 18, 1999.

Herzog, H. J. 1998. "The Economics of CO_2 Capture," presented at the Fourth International Conference on Greenhouse Gas Control Technologies, Interlaken Switzerland, August 30–September 2.

Herzog, H. J., ed., 1998. *Proceedings of the Stakeholders' Workshop on Carbon Sequestration*, MIT EL 98-002, Massachusetts Institute of Technology Energy Laboratory, June.

IEA (International Energy Agency) 1998. *Carbon Dioxide Capture from Power Stations*, available at www.ieagreen.org.uk/sr2p.htm.

Socolow, R., ed. 1997. *Fuels Decarbonization and Carbon Sequestration: Report of a Workshop*, Report 302, Princeton University/ Center for Energy and Environmental Studies, September.

Valencia, J. A., and R. D. Denton 1985. "Method and Apparatus for Separating Carbon Dioxide and Other Acid Gases from Methane by the Use of Distillation and a Controlled Freezing Zone," U.S. Patent 4,533,372, August 6.

Victory, D. J., and J. A. Valencia 1987. "The CFZ Process: Direct Methane–Carbon Dioxide Fractionation," presented at the 66th annual Gas Processors Association Convention, Denver, Colo., March.